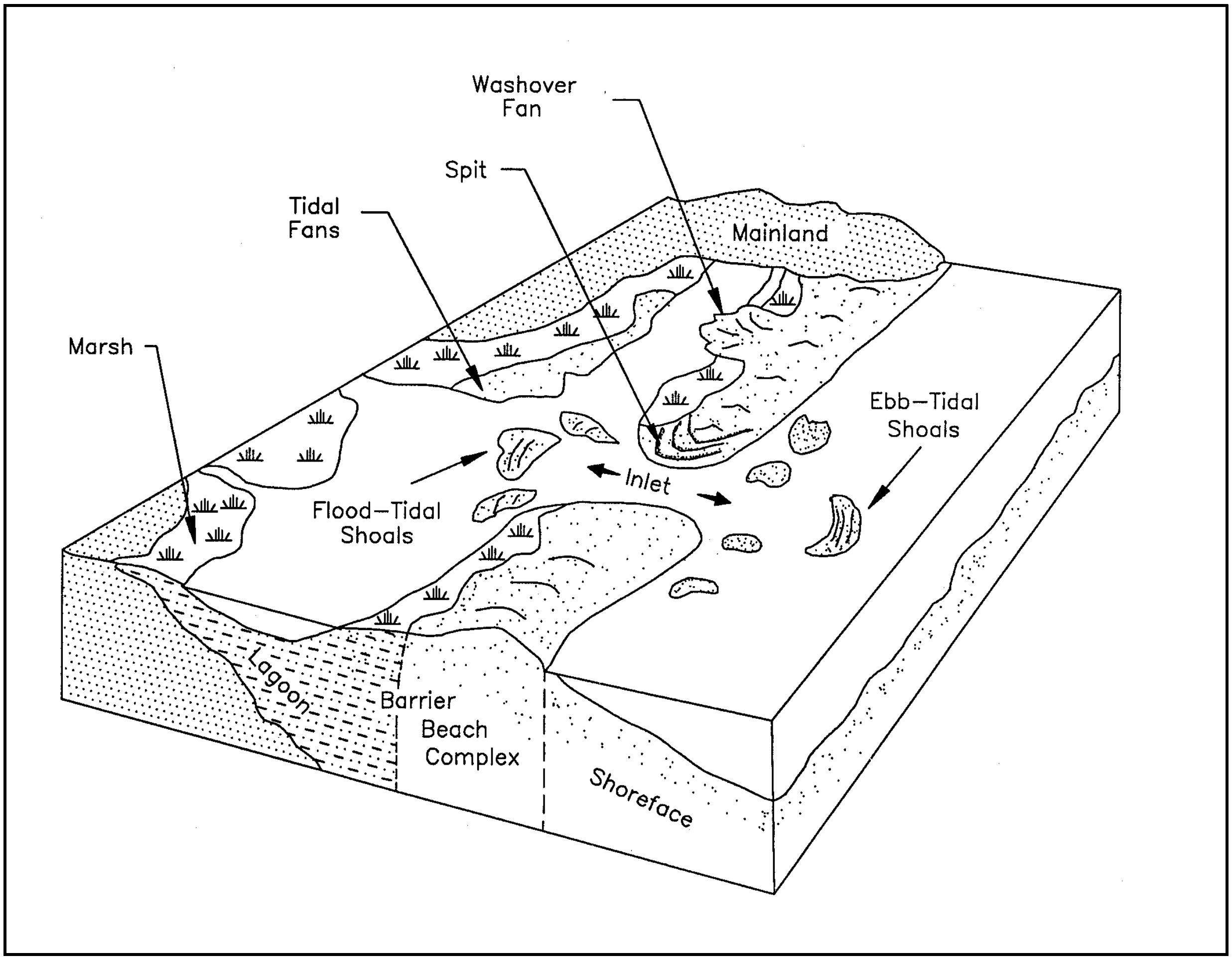

Figure IV-2-24. A three-dimensional view of features commonly found in barrier island systems, including the back barrier, overwash fans, and lagoons. The lagoons often become estuaries, particularly if sediment is supplied by both rivers and inlets

(4) The long-term and widespread interest in barrier islands is largely due to their great economic importance. Ancient buried barriers are important petroleum reservoirs. Contemporary barriers protect lagoons and estuaries, which are the breeding grounds for many marine species and birds. In addition, barrier islands are among the most important recreational and residential regions. In recent years, man's adverse impact on these fragile ecological and geological environments has led to increased need to study their origins and development to improve coastal management and preserve these critical resources for the future.

(5) An enormous literature on barrier islands exists. Nummedal (1983) provides a readable and concise overview. Leatherman's (1979) book is a compilation of papers on U.S. east coast and Gulf of Mexico barriers. Many seminal papers on barrier island evolution have been reprinted in Schwartz (1973). Textbooks by Carter (1988), Davis (1985), King (1972a), and Komar (1976) discuss barriers and include voluminous reference lists. Classic papers on beach processes have been reprinted in Fisher and Dolan (1977).

b. Distribution of barrier coasts. Barrier islands are found around the world (Table IV-2-2). They are most common on the trailing edges of the migrating continental plates (Inman and Nordstrom 1971)[1]. This type of plate boundary is usually non-mountainous, with wide continental shelves and coastal plains. Over 17 percent of the North American coastline is barrier, most of it along the eastern seaboard facing the Atlantic Ocean and the Gulf of Mexico. Table IV-2-3 lists the lengths of barriers and spits in the United States. Of the Atlantic states, Maine and New Hampshire have the fewest barriers because their coasts are largely composed of igneous rock. Massachusetts, with mostly glacial moraines and outwash along the coast, has the surprising total of 184 km of spits and barriers. Of the continental states, Florida has the most barriers and spits, totaling over 1,000 km for both the Atlantic and the Gulf of Mexico. Most of the shorelines facing the Gulf of Mexico consist of barrier islands. A portion of Florida's west coast, where wave energy is low, is mangrove swamp, but the Panhandle is famous for its glistening white barriers.

Table IV-2-2
Worldwide Distribution of Barrier Island Coasts

Continent	Barrier Length (km)	% of World Total Barriers	% of Continent's Coastline that is Barrier
N. America	10,765	33.6	17.6
Europe	2,693	8.4	5.3
S. America	3,302	10.3	12.2
Africa	5,984	18.7	17.9
Australia	2,168	6.8	11.4
Asia	7,126	22.2	13.8
Total	32,038	100.0	

From Cromwell (1971)

Almost the entire shore of Texas consists of long barriers, which continue south into Mexico. Extensive barriers are also found on the Gulf of Alaska north of Bering Strait. Including numerous spits in the Aleutians and the Gulf of Alaska, the state of Alaska has almost 1,300 km of barrier in total, exceeding Florida. The United States total shown in Table IV-2-3 is 4,882 km, about half the North American total computed by Cromwell (1971). For more information, the most extensive survey of United States barriers was documented in the *Report to Congress: Coastal Barrier Resources System* (Coastal Barriers Study Group 1988).

c. General coastal barrier structure. The barrier shore type covers a broad range of sizes and variations. Three general classes of barrier structures can be identified (Figure IV-2-25):

(1) Bay barriers - connected to headlands at both ends and enclosing a bay or wetland.

(2) Spits - attached to a sediment source and growing downdrift. May be converted to a barrier island if a storm cuts an inlet across the spit. May evolve into bay barriers if they attach to another headland and completely enclose a lagoon.

[1] *The trailing edge* of a continent is moving away from an active spreading center. For example, the Atlantic coast of the United States is a trailing edge because new seafloor is being formed along the mid-Atlantic ridge, causing the Atlantic Ocean to grow wider (Figure IV-1-2). The Pacific coast is a *leading edge* because the oceanic plates are being subducted (consumed) at various trenches and are therefore becoming smaller.

Table IV-2-3
Barrier Islands and Spits of the United States

Ocean or Sea	State	Total Length (km)[1]
Atlantic	Maine	11.4
	New Hampshire	2.5
	Massachusetts [2]	184.4
	Rhode Island [3]	17.6
	New York [4]	152.2
	New Jersey	106.0
	Delaware [5]	33.7
	Maryland [5]	49.2
	Virginia [5]	126.0
	North Carolina	380.7
	South Carolina	234.2
	Georgia	159.0
	Florida	533.3
	Atlantic coast total	**1990**
Gulf of Mexico	Florida	478.5
	Alabama	92.7
	Mississippi	59.5
	Louisiana	151.9
	Texas	498.0
	Gulf of Mexico total	**1281**
Pacific - Continental USA	Washington [6]	63.9
	Oregon	91.9
	California	65.4
	Pacific total	**221**
Beaufort, Chukchi, Bering Seas, Gulf of Alaska, Bristol Bay	Alaska total (incl. Aleutians)	**1266**
Lakes Superior, Huron, Michigan, Ontario, Erie	Combined Great Lakes states	**124**
United States total [2,3,4,5,6]		**4882**

Source: Unpublished data generated during the Corps of Engineers' Barrier Island Sediment Study (BISS), 1989.
[1] Length of barriers measured from U.S. Geological Survey topographic maps. Includes barriers and spits enclosing a body of water or marsh, not the total length of beaches in the United States. No data available for Puerto Rico, Virgin Islands, Pacific Trust Territories.
[2] Includes Nantucket and Martha's Vineyard Islands.
[3] Does not include Narragansett Bay.
[4] Atlantic Ocean only; does not include spits in Long Island Sound or Great Peconic Bay.
[5] Does not include Chesapeake Bay.
[6] Includes spits in Strait of Juan de Fuca. Does not include Long Beach Peninsula, enclosing Willapa Bay.

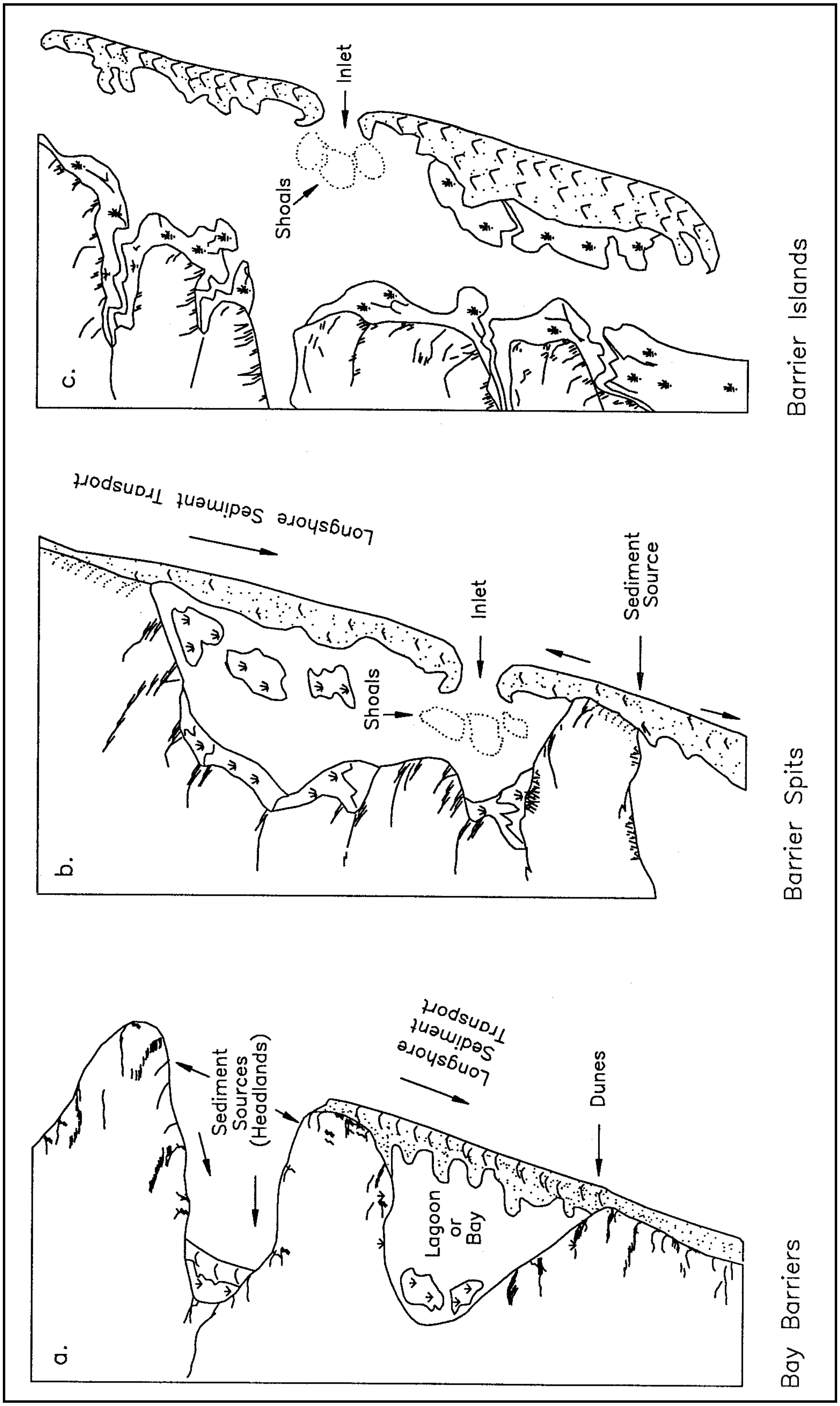

Figure IV-2-25. General barrier types: bay, spit, and island

(3) Barrier islands - linear islands that are not attached to the mainland but that enclose a bay, pond, or marsh/wetland. A series of these islands extending along the coast are defined as a barrier chain.

d. Origin and evolution. The origin of barrier islands has been a topic of debate among geologists for over a century (Schwartz 1973). The differing theories suggest that there are probably several types of barriers, each undergoing its own form of development due to unique physical and geologic factors. Three main theories have evolved, all of which have fierce supporters and critics.

(1) Emergence model. De Beaumont in 1845 was the first naturalist formally to present a theory of barrier island formation. It was supported and modified by the influential Johnson (1919). These researchers theorized that barrier emergence began with the formation of an offshore sand shoal, which consisted of material reworked from the seafloor by waves. Over time, the shoal would accumulate ever more sand and grow vertically, eventually emerging above the sea surface (Figure IV-2-26). Wave swash and wind deposition would continue to contribute sand to the shoal, allowing it to grow larger and larger. Hoyt (1967) objected to this hypothesis because he was unaware of any examples of bars emerging above water and surviving wave action, although the growth of submerged bars was well-recorded. Otvos (1970) reported evidence from the Gulf coast supporting the emergence of submarine shoals (he conveniently noted that subsequent migration of barriers might completely obscure the conditions of formation of the original barrier).

(2) Submergence model. The submergence concept was refined by Hoyt (1967) and has received much support. In this model, the initial physical setting is a mainland beach-and-dune complex with a marsh separating the beach from higher terrain inland. Rising sea level floods the marsh, creating a lagoon that separates the beach from the mainland (Figure IV-2-27). Presumably, usually the sea level rise is part of a worldwide pattern (eustatic), but it may be caused in part by local submergence. Once formed, maintenance of the barrier becomes a balance of sediment supply, rate of submergence, and hydrodynamic factors.

(3) Spit detachment model. The third major model calls for the growth of sandspits due to erosion of headlands and longshore sediment transport (Figure IV-2-28). Periodically, the spit may be breached during storms. The furthest portion of the spit then becomes a detached barrier island, separated by a tidal inlet from the portion that is still attached to the mainland. Gilbert (1885) may have been the first geologist to suggest the spit hypothesis, based on his studies of ancient Lake Bonneville, but the hypothesis lay dormant for many years because of Johnson's (1919) objections. In recent years, it has received renewed support because the cycle of spit growth and breaching can be seen in many locations (for example, at Cape Cod, Massachusetts (Giese 1988)).

(4) Combined origin model. Schwartz (1971) concluded that barrier island formation is most probably a combination of all of the above mechanisms. He felt that only a few examples of barriers could be cited as having been formed by only one method. Most systems were much more complex, as demonstrated by the barriers of southern Louisiana, which were formed by a combination of submergence and spit detachment (Penland and Boyd 1981).

e. Barrier response to rising sea level.

(1) Many of the barriers in the United States, particularly along the Atlantic coast, are eroding, causing serious economic and management challenges. What is responsible for this erosion?

(2) Sea level and sediment availability are probably the major factors that determine barrier evolution (Carter 1988). Three sea level conditions are possible: rising, falling, and stationary. Rising and falling sea

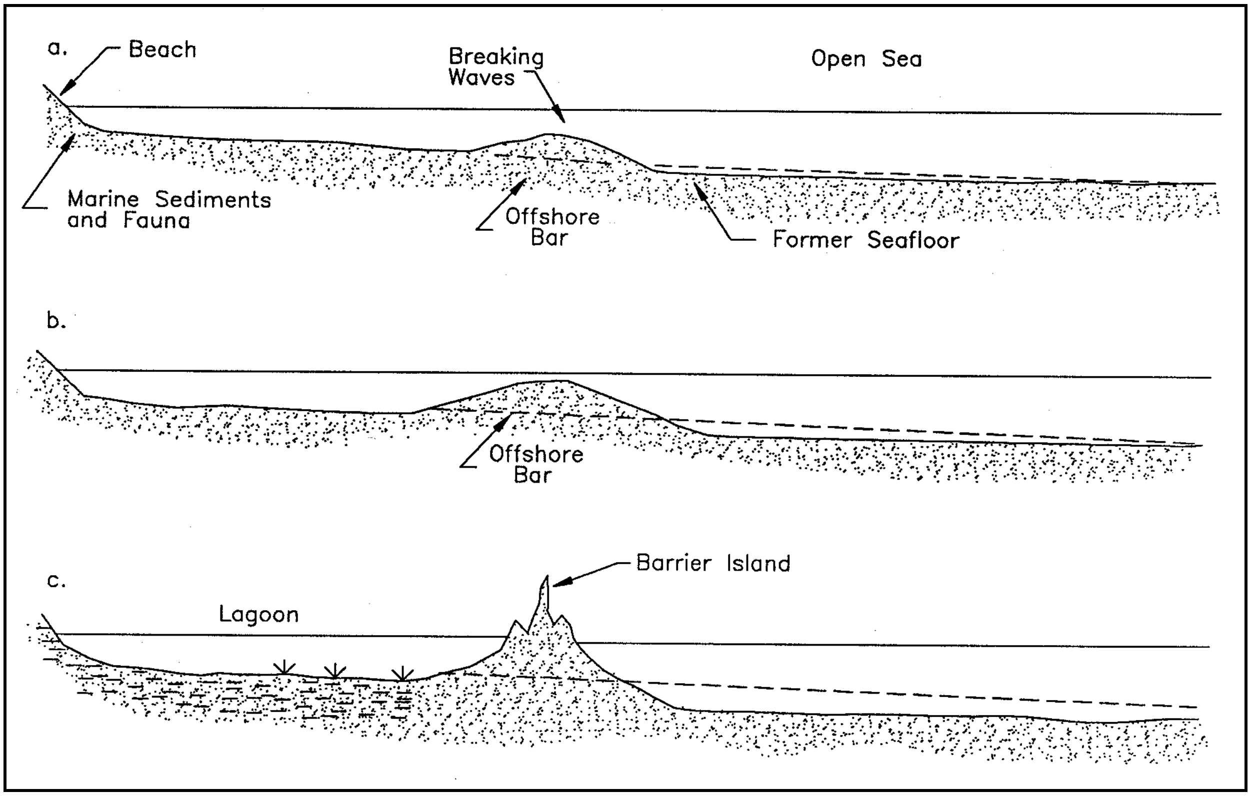

Figure IV-2-26. Emergence model of barrier island formation (modified from Hoyt (1967)), (a) Waves erode the seafloor, forming a sandbar, (b) The bar continues to grow higher and wider, (c) Bar is converted to an island, enclosing a lagoon on the landward side

usually result in great sediment movement as barriers adjust. A stationary stage, however, allows the shore to adjust slowly and achieve equilibrium between sediment supply and dynamic processes. Commonly, if sea level rises and sediment supply is constant, a barrier retreats (*transgression* of the sea). On the other hand, if sea level is rising but a large amount of sediment is supplied locally by rivers or eroding headlands, a particular barrier may be stable or may even aggrade upwards (see Table IV-1-6). However, many other factors can intervene: local geological conditions, biological activity, susceptibility to erosion, the rate of sea level change. Therefore, each location must be evaluated individually.

(3) Given the condition of rising sea level along the eastern United States, what are the mechanisms that cause barrier retreat? Three models of shoreline response to rising sea level have been proposed (Figure IV-2-29). These assume that an equilibrium profile is maintained as the shoreline is displaced landward and upward. In addition, overall sediment budget is balanced and energy input is constant.

(a) The first model, often called the Bruun Rule (Bruun 1962), assumes that sediment eroded from the shoreface is dispersed offshore. As water level rises, waves erode the upper beach, causing the shoreline to recede. Conceptually, this erosion supplies sediment for upward building for the outer part of the profile. The model assumes that the initial profile shape will be reestablished farther inland but at a height above the original position equal to the rise in water level z. Therefore, the retreat of the profile x can be calculated from the following relationship (a modified version of the Bruun Rule):

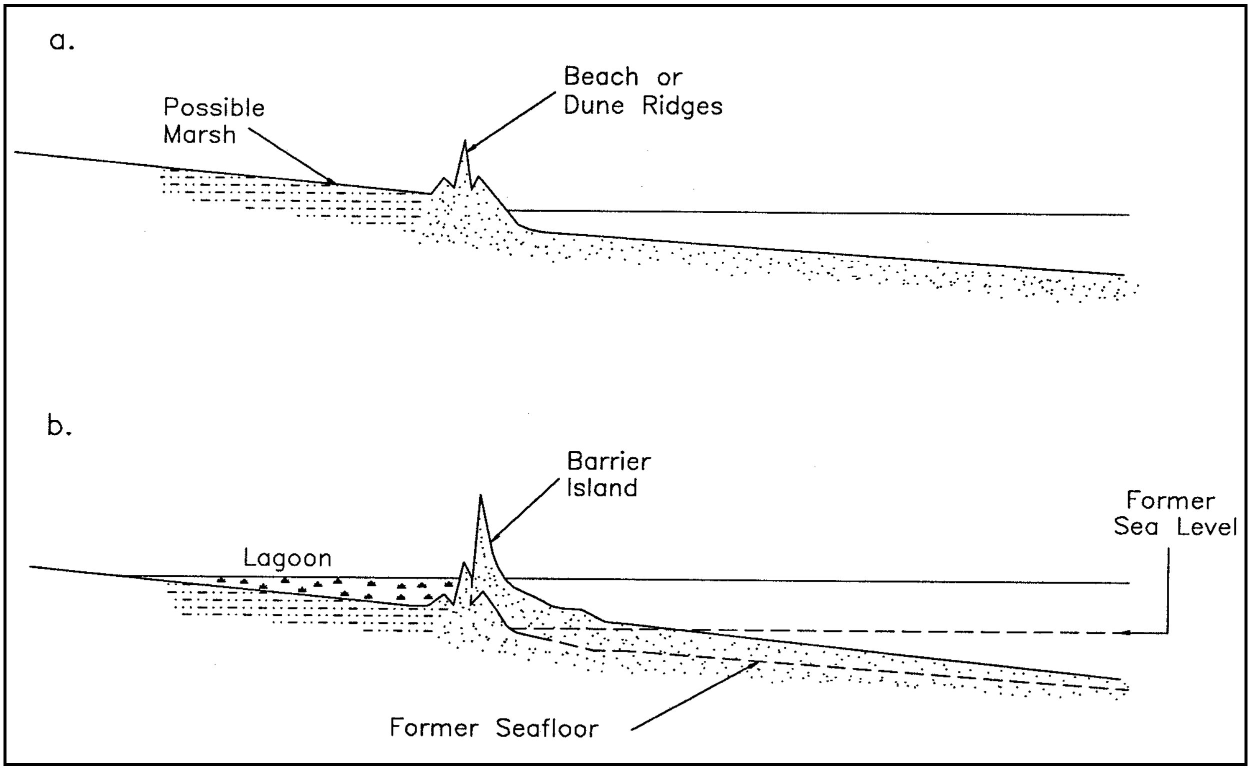

Figure IV-2-27. Submergence model of barrier island formation (modified from Hoyt (1967)), (a) Beach or sand dune ridges form near the shoreline, (b) Rising sea level floods the area landward of the ridge, forming a barrier island and lagoon. Sediment must be available to allow the island to grow vertically as sea level rises

$$x = \frac{zX}{Z} \qquad \text{(IV-2-1)}$$

where the terms *x, z, X,* and *Z* are shown in Figure IV-2-29a. Attempts to verify the Bruun rule have been ambiguous, and modifications to the model have been proposed (Dolan and Hayden 1983). The most successful studies required long-term data sets, such as the profiles from Lake Michigan examined by Hands (1983). His research showed that the shoreface profile requires a considerable time (years or decades) to adjust to water level changes. It is unclear whether the Bruun Rule would apply if an ample supply of sediment were available during rising sea level. Would the barrier essentially remain in place while sand eroded from the shoreface or newly supplied sand was dispersed offshore to maintain the profile? The Bruun Rule and some of its underlying assumptions are discussed in greater detail in Part IV-3.

(b) Landward migration of a barrier by the rollover model applies to coasts where washover processes are important. As sea level rises, material is progressively stripped from the beach and shoreface and carried over the barrier crest by waves. The sand is deposited in the lagoon or marsh behind the barrier (Figure IV-2-30). Dillon (1970) documented this process along the southern Rhode Island coast. As the barrier moves landward (rolls over itself), lagoonal sediments may eventually be exposed on open shoreface. Evidence of this can be seen in Rhode Island during winter storms, when large pieces of peat are thrown up on the beach. Dingler, Reiss, and Plant (1993) have described a model of beach erosion and overwash deposition on the Isles Dernieres, off southern Louisiana. They attributed a net annual beach retreat of

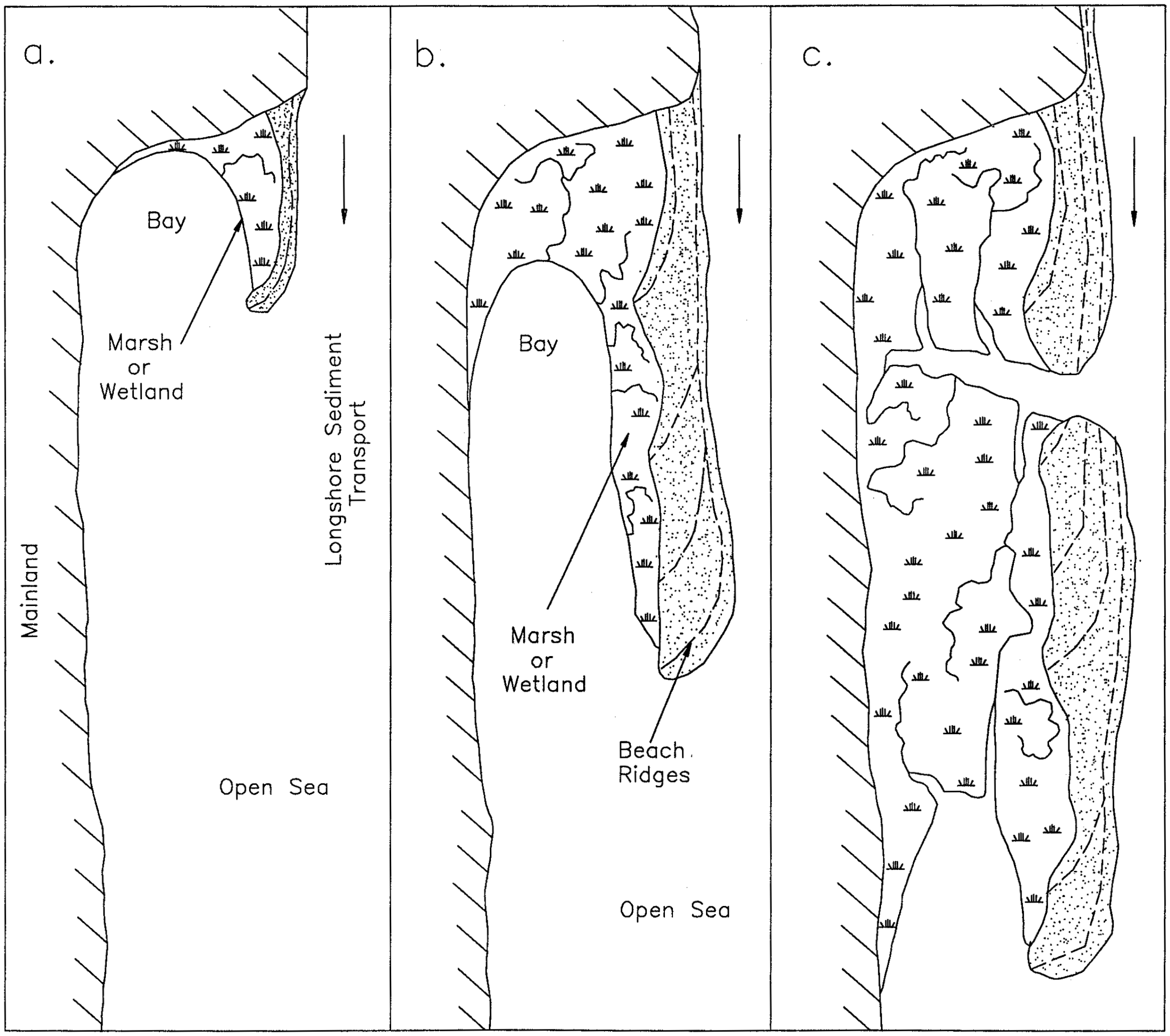

Figure IV-2-28. Barrier island formation from spit (modified from Hoyt (1967)), (a) Spit grows in direction of longshore drift, supplied from a headland, (b) Spit continues to grow downdrift, marsh begins to fill semi-protected bay, (c) Part of spit is breached, converting it to a barrier island

greater than 10 m/yr to winter cold-front-driven storms that removed sediment from the beach face and infrequent hurricanes that shifted a substantial quantity of sediment to the backshore. For the most part, rollover is a one-way process because little of the sand carried over the barrier into the lagoon is returned to the open shoreface.

(c) The barrier overstepping model suggests that a barrier may be drowned, remaining in place as sea level rises above it. Several hypotheses have been proposed to explain how this process might occur:

- If the rate of sea level rise accelerates, the barrier may be unable to respond quickly by means of roll-over or other mechanisms. Carter (1988) cites research that suggests that gravel or boulder barriers are the most likely to be stranded.

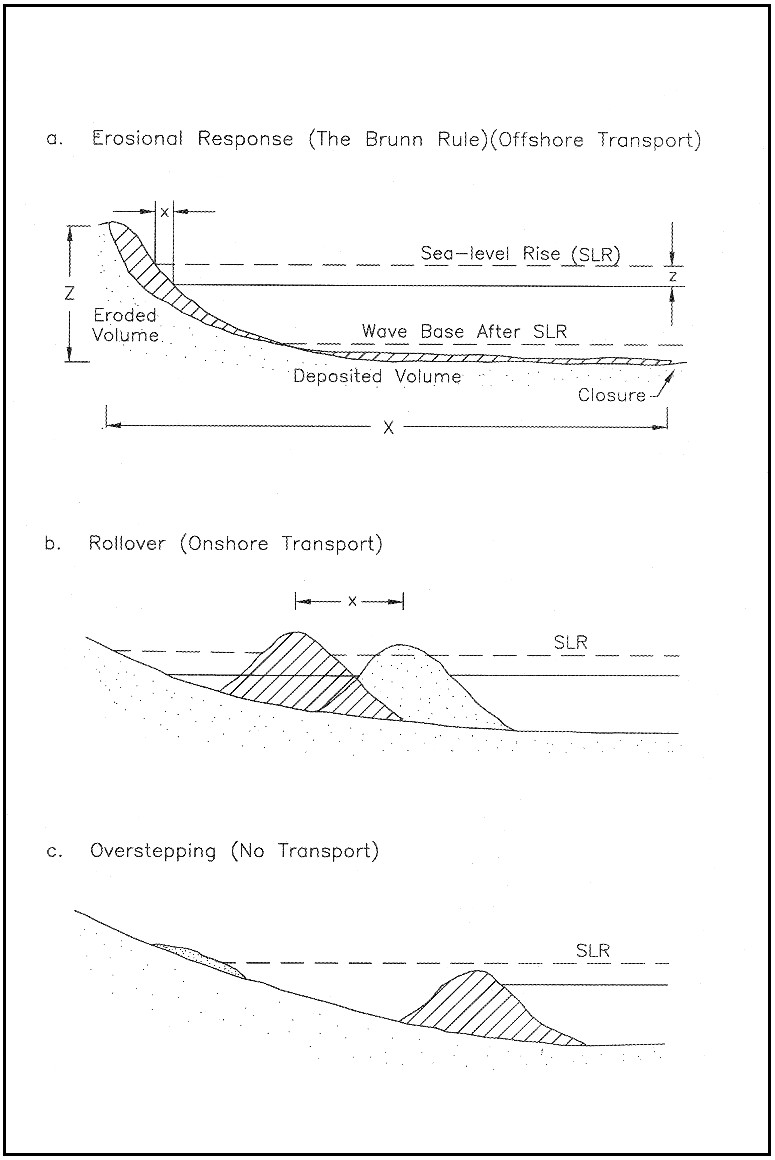

Figure IV-2-29. Three models of shoreline response to sea level rise: (a) Erosional response model/Bruun Rule assumes offshore dispersal of eroded shoreline materials; (b) Island rollover model assumes that barriers migrate landward according to the rate of sea level rise; (c) Overstepping model assumes submergence in place (adapted from Carter (1988))

- A modest influx of sediment may retard barrier migration enough to allow overstepping. If a constant volume of sediment is available, the new material must be distributed over a wider and wider base as sea level rises. The result is that vertical growth per unit time decreases. Eventually, the barrier is overtopped and the surf zone jumps forward to the bay shoreline that was formerly protected.

Figure IV-2-30. Westhampton Beach, Long Island, New York (March 1994 - view looking north towards Moriches Bay). In December 1992, the barrier island breached here during a northeaster, and 60 houses were destroyed. A large overwash fan can be seen in the bay, and to the left are houses that survived the storm. This is an example of the rollover mechanism, when sand from the ocean-facing shoreface is carried over the barrier and deposited in the back bay. The breach was repaired by the Corps of Engineers during 1993 using sand dredged from offshore. This low stretch of the barrier is particularly vulnerable, with several earlier breaches on record. In summer 1998, new homes were again being built here

- A barrier may remain in place because of a dynamic equilibrium that develops between landward and seaward sediment transport. As sea level rises, tidal prism of the lagoon increases, resulting in more efficient ebb transport. During this time, an increasing amount of washover occurs, but the effect is counteracted because sediment is being returned to the exposed shoreface. If little or no new sediment is added to the system, the sea eventually rises above the barrier crest, allowing the surf zone to jump landward to a new location (the formerly protected mainland shore).

- All three of these mechanisms may come into play at various times, depending upon environmental conditions. Sediment supply may be the crucial factor, however. Some stranded barriers, such as the ones in the northeastern Gulf of Mexico, may have maintained vertical growth because of an adequate sediment supply (Otvos 1981).

(4) In all likelihood, barriers respond to all three of the migration models, depending upon timing and local conditions such as sediment supply or preexisting topography (Carter 1988). During the initial stages of sea level rise, the shore erodes and material is dispersed offshore (the Bruun Rule). As the barrier becomes narrower, washover carries more and more sediment to the back lagoon. Eventually, the barrier may become stranded and be drowned. These models have been criticized because they are two-dimensional and do not account for variations in longshore drift. The criticisms are valid because drift is sure to vary greatly as barriers are progressively reshaped or drowned. As a result, pockets of temporarily prograding barriers may remain along a generally retreating coastline.